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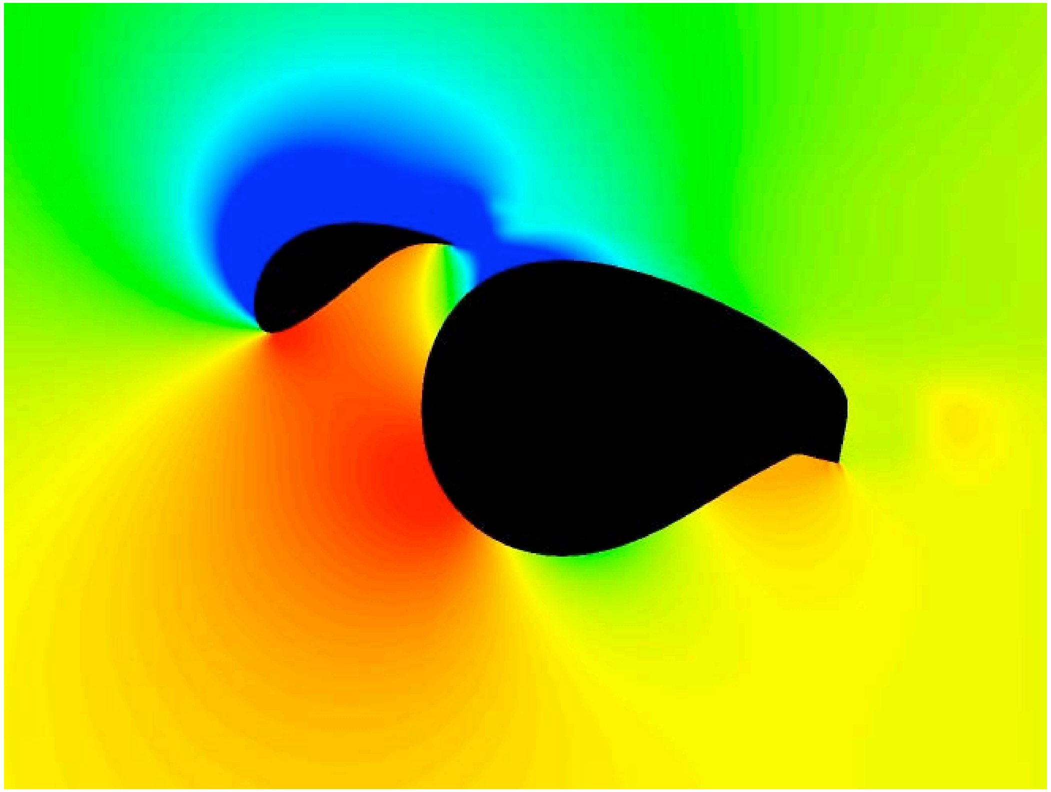
Mac Gaunaa, Frederik Zahle, Niels N. Sørensen, Christian Bak, Pierre-Elouan Réthoré

Wind Energy Department, DTU Wind Energy, DK-4000 Roskilde, Denmark

Outline

- Introduction & Motivation
- Methods used in this work
- Reference rotor
- Results & Discussion
- Conclusions & Outlook



Introduction & motivation

- Conventional Blade Element Momentum based design methods result in too lightly loaded inner part of rotors for maximum energy capture
- The inner part of wind turbine blades have a high relative thickness due to structural/load/cost constraints
- This results in poor aerodynamic performance on the inner part of the rotors

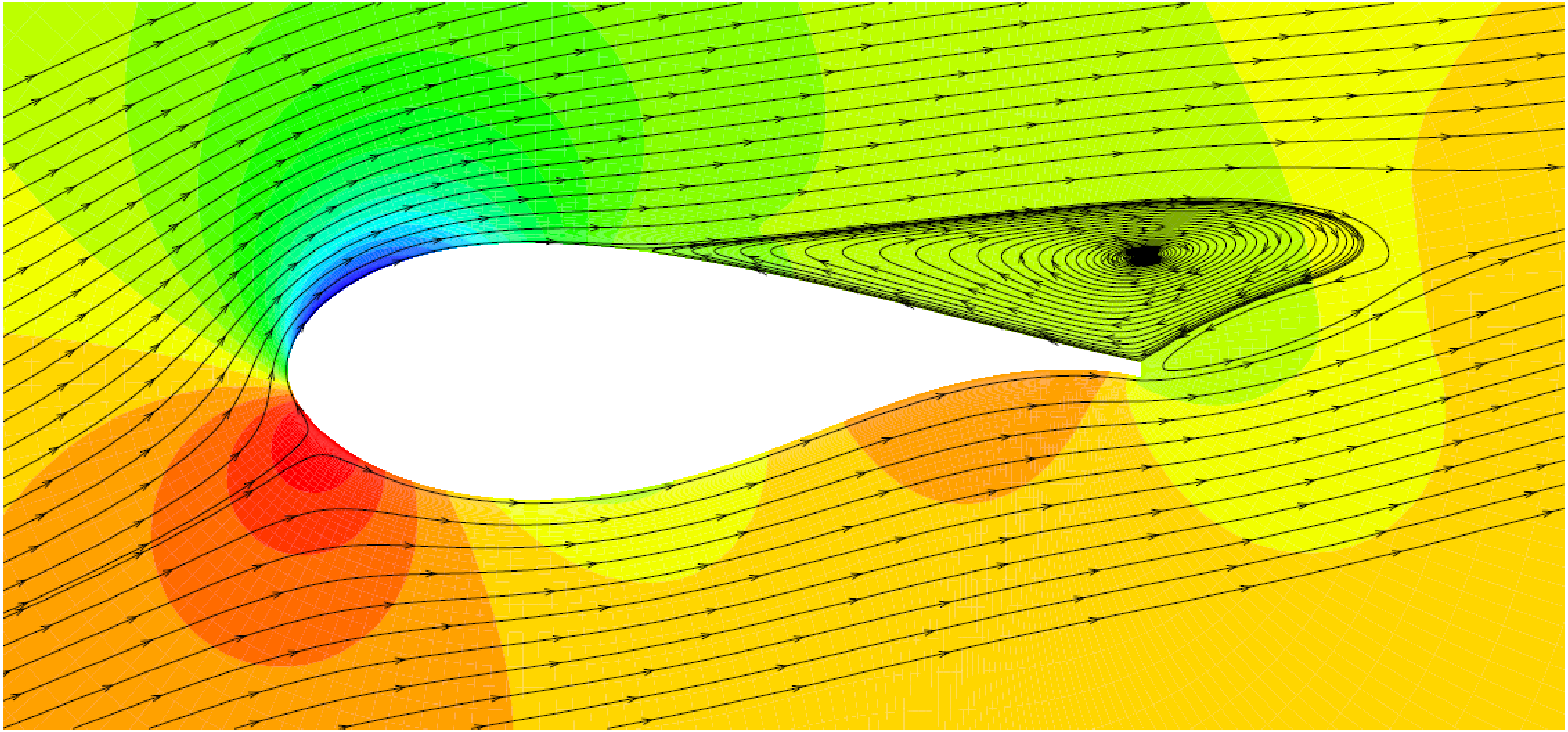
- Earlier findings have shown that it is possible to increase the performance of (very) thick 2D airfoils drastically using leading edge slats

- **What if we try to tap into this unused power production potential using leading edge slats?**
- **How do we do that?**
- **What could be gained from it?**

Introduction

Flow behavior for a ”thick” main airfoil alone

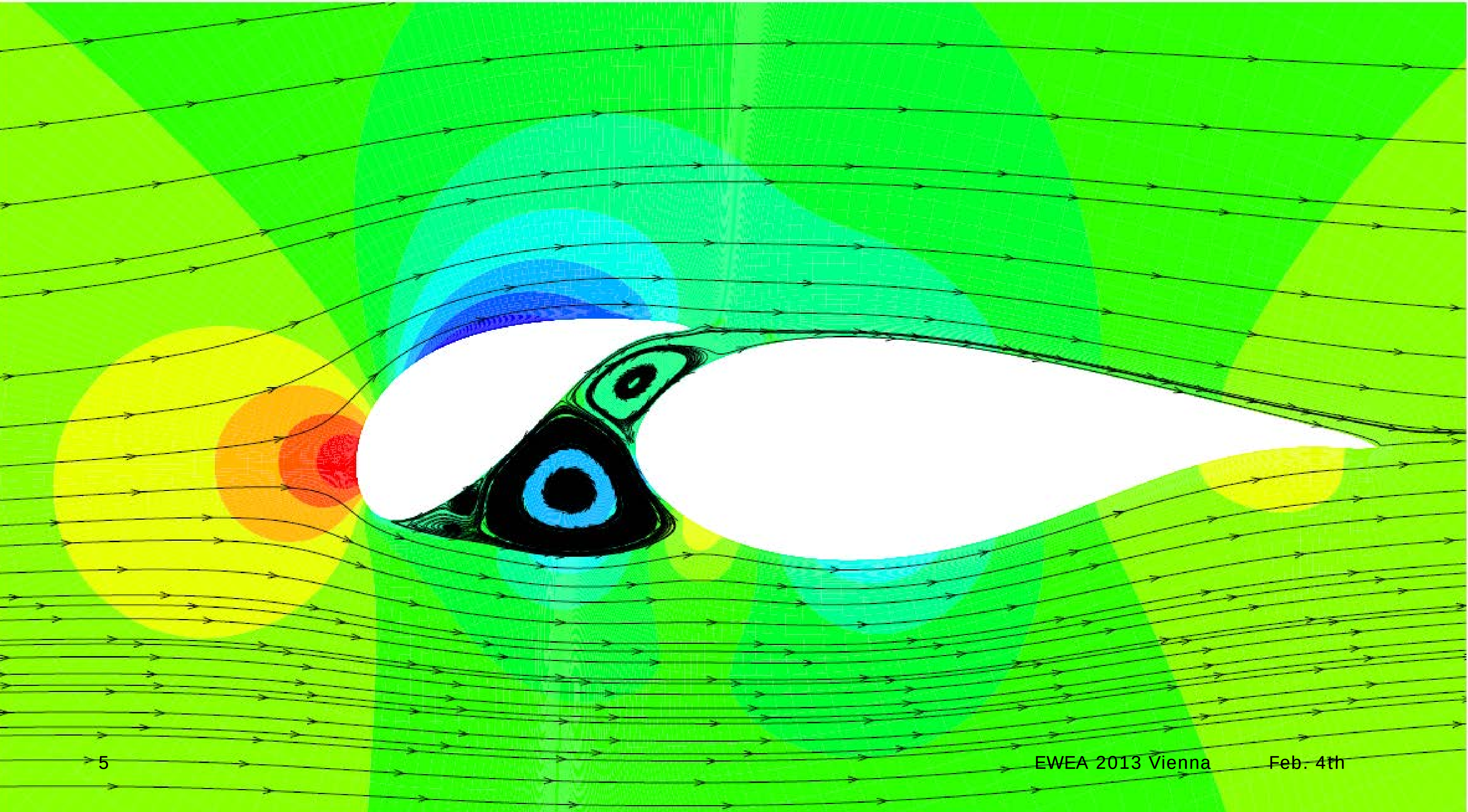
Main Airfoil, Re=1e6, AOA=16 deg.



Introduction

Flow behavior example: $\alpha=2^0$

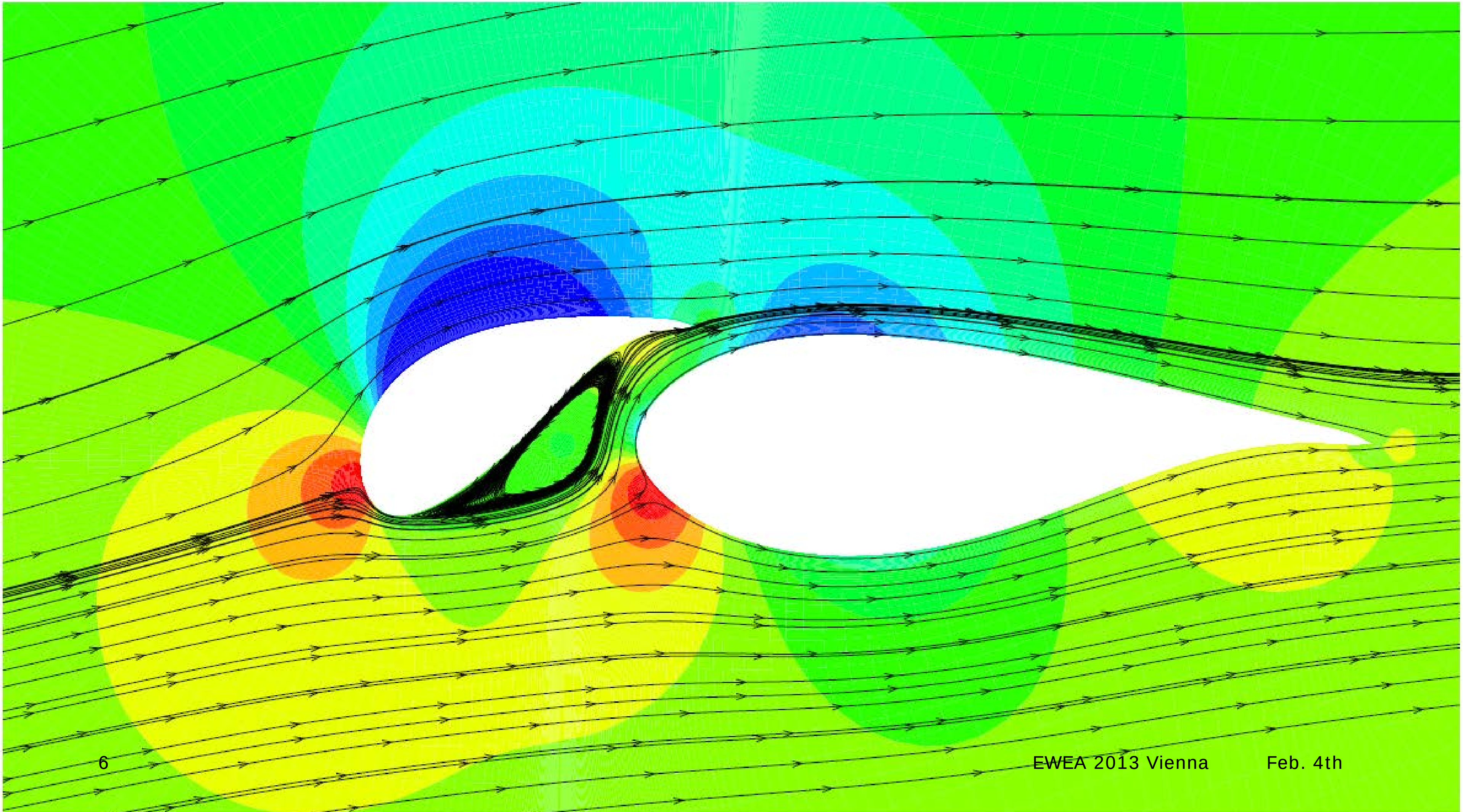
- Pressures and streamlines $Re=1*10^6$



Introduction

Flow behavior example: $\alpha=8^0$

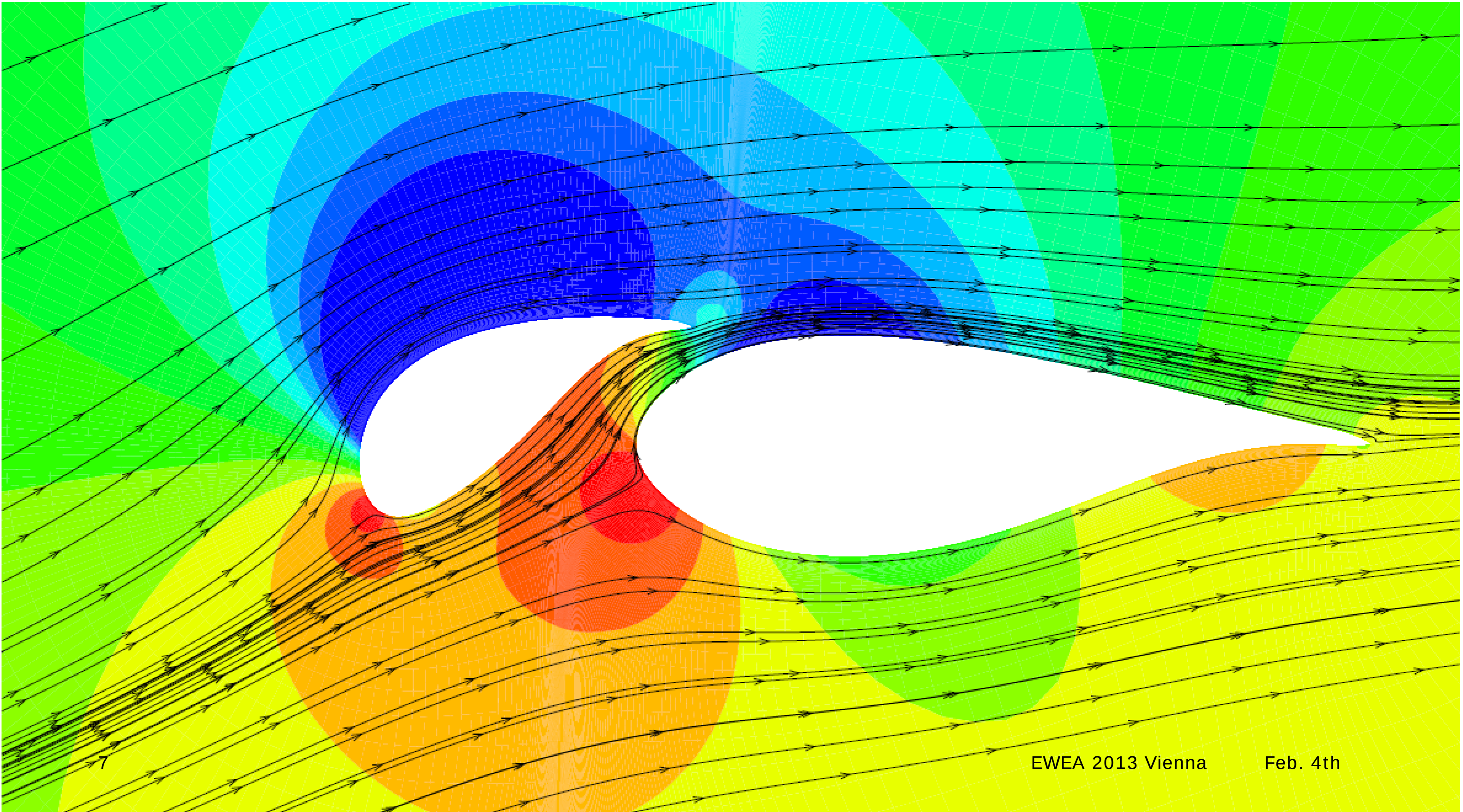
- Pressures and streamlines $Re=1*10^6$



Introduction

Flow behavior example: $\alpha=14^0$

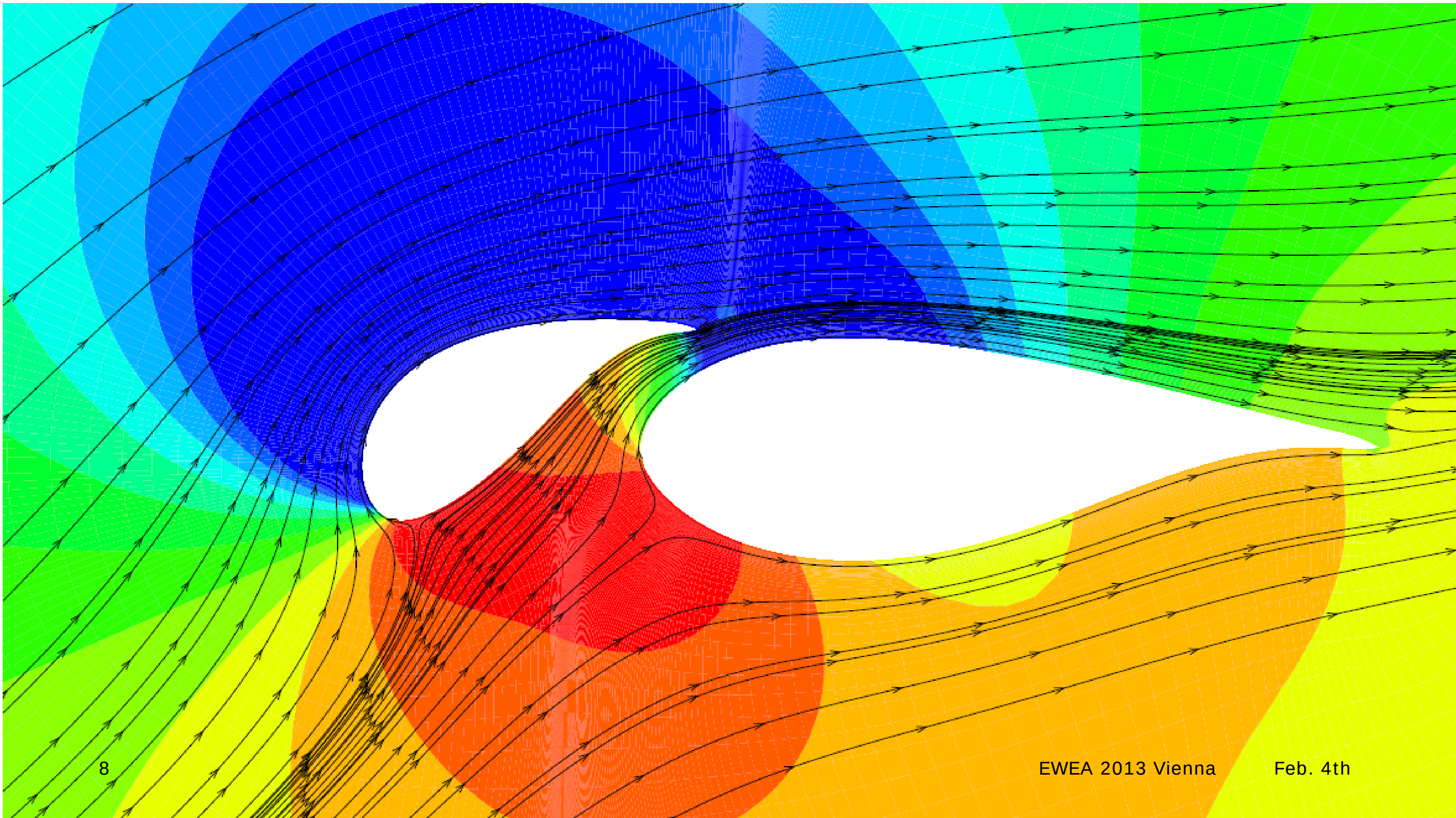
- Pressures and streamlines $Re=1*10^6$



Introduction

Flow behavior example: $\alpha=24^0$

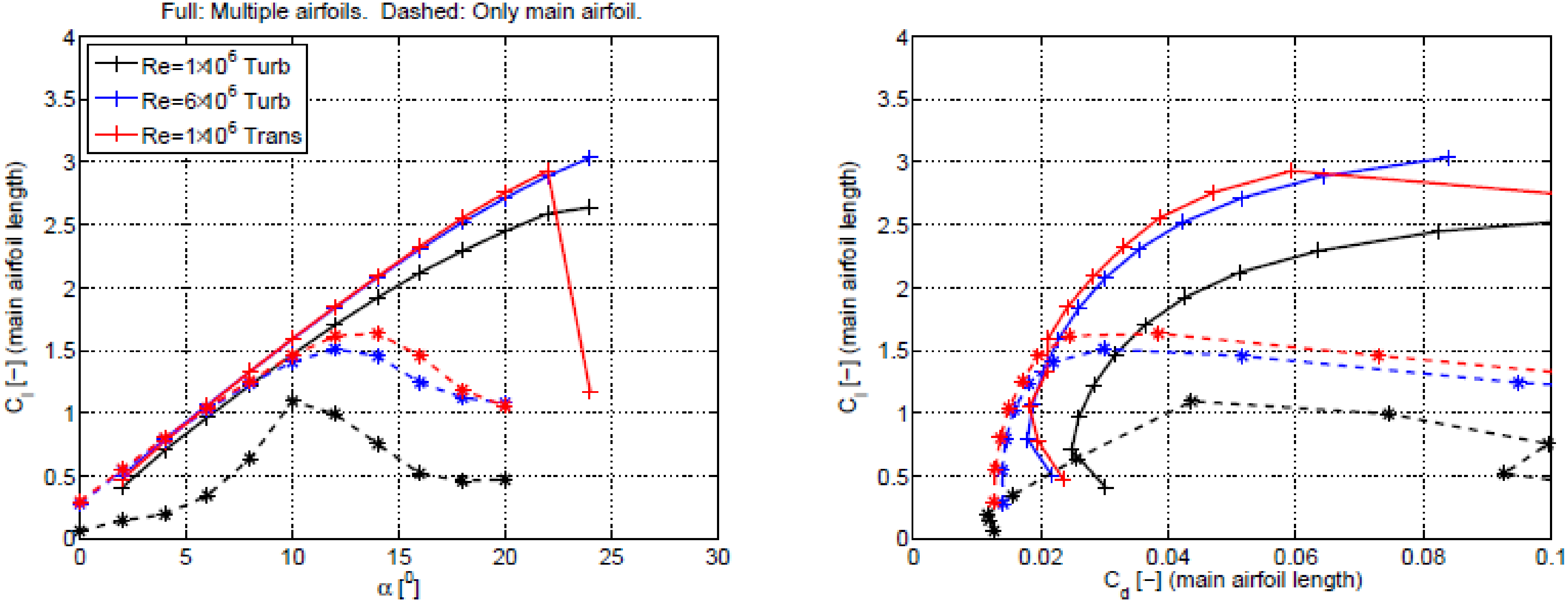
- Pressures and streamlines $Re=1*10^6$



Introduction

An example of lift and drag

$c_s/c=0.3$, results from Torque 2010, Gaunaa et.al.



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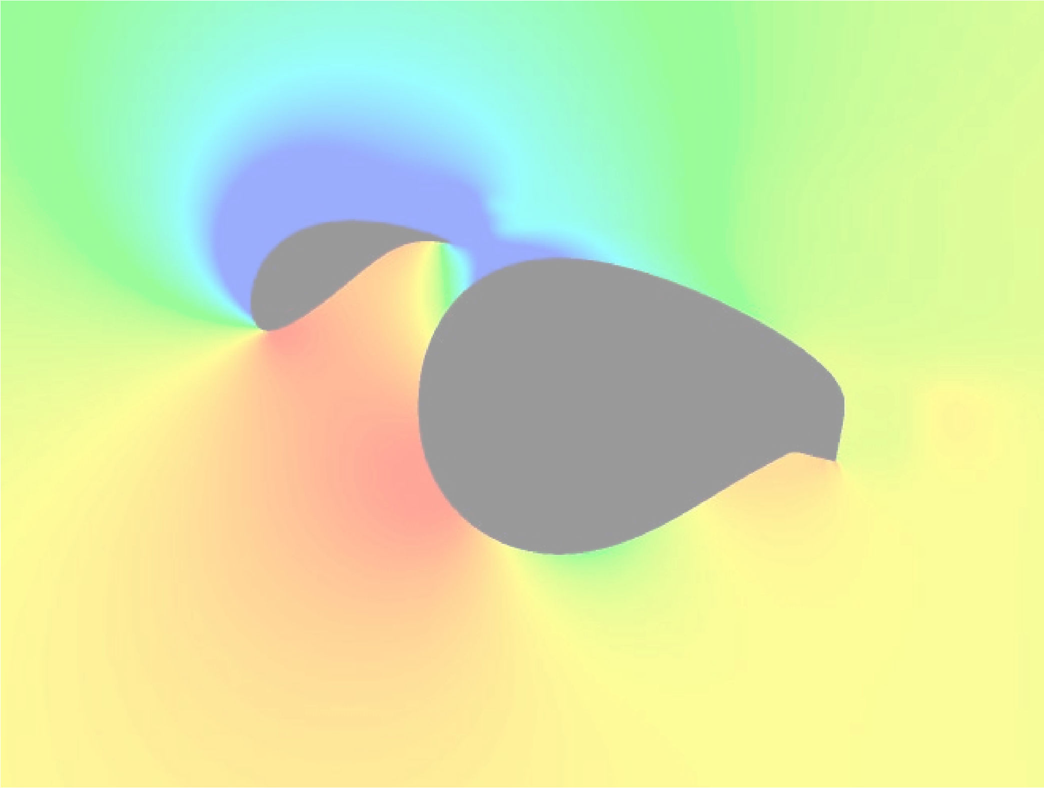
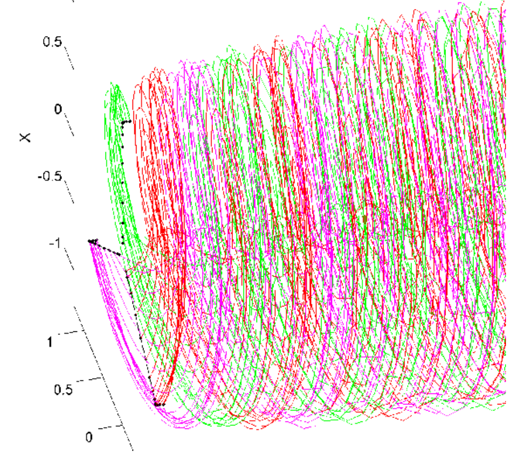
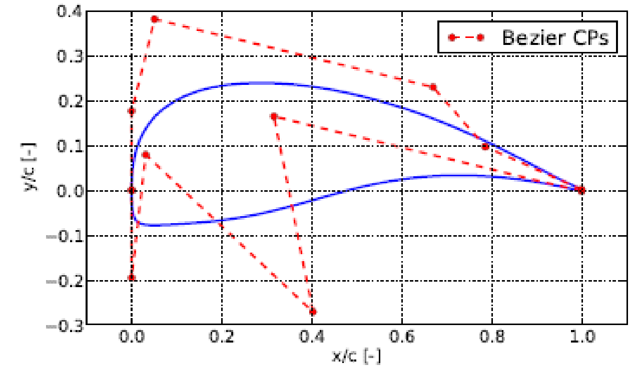


Methods & Tools



- **Rotor design**
  - Based on Lifting Line free wake method results
  - Specified $\Gamma(r) \Rightarrow d\mathbf{F}/dr(r)$ and flow angle
- **2D optimization framework**
  - A coupling of
    - Optimization: OpenMDAO
    - Airfoil representation using Bezier splines
    - 2D CFD
    - $-Cost = K_{opt} C_l/C_d(\alpha^* - \Delta\alpha)/A + (1-K_{opt}) C_l(\alpha^*)/B$
    - 17 design variables: α^*(1), slat TE pos(2), slat angle(1) & slat shape(13)



- **CFD solver EllipSys2D/3D**
  - Used for optimization (2D) and evaluation of the design (3D)
  - Incompressible RANS solver using structured curvilinear grids
  - k-ω SST turbulence model, Overset method used in 3D for the slats
  - Validated performance with multi element airfoils in 2D for the AGARD test case

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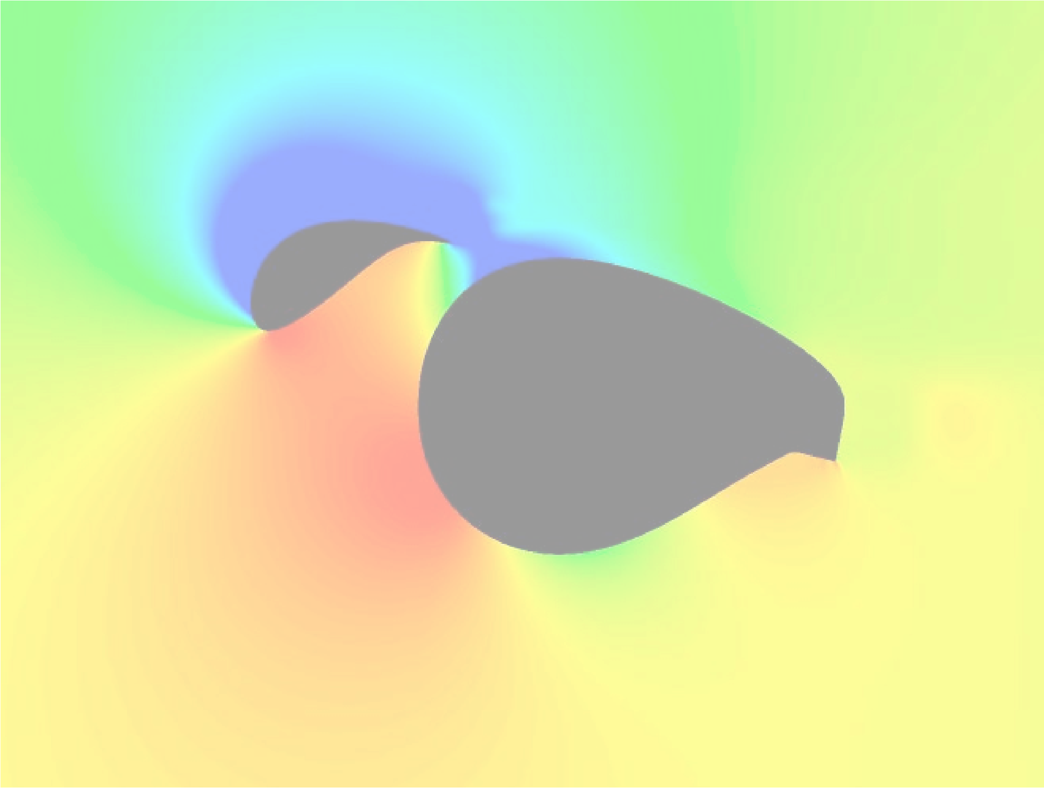

Reference rotor and setup

- DTU 10MW reference rotor (Light Rotor, Inn Wind)
- State of the art, “realistic rotor”, based on FFA-W3-XXX airfoils
  - 3 bladed PRVS rotor, 10MW
  - R=89.16M
  - Rated wind speed 11.5 m/s
  - Optimal Tip Speed Ratio is λ=7.5

- We allow a retwisting of the radial locations where the slats are located, but otherwise do not change the reference blade
- Slats are designed for $0.1 \leq r/R \leq 0.3$ $0.08 \leq r/R \leq 0.32$
- Chordlength ratios and main airfoil thickness ratios are given below

r/R	0.1	0.15	0.175	0.2	0.25	0.3
c_{slat}/c_{main}	0.54	0.52	0.50	0.35	0.20	0.20
t/c_{main}	0.94	0.77	0.67	0.58	0.45	0.38

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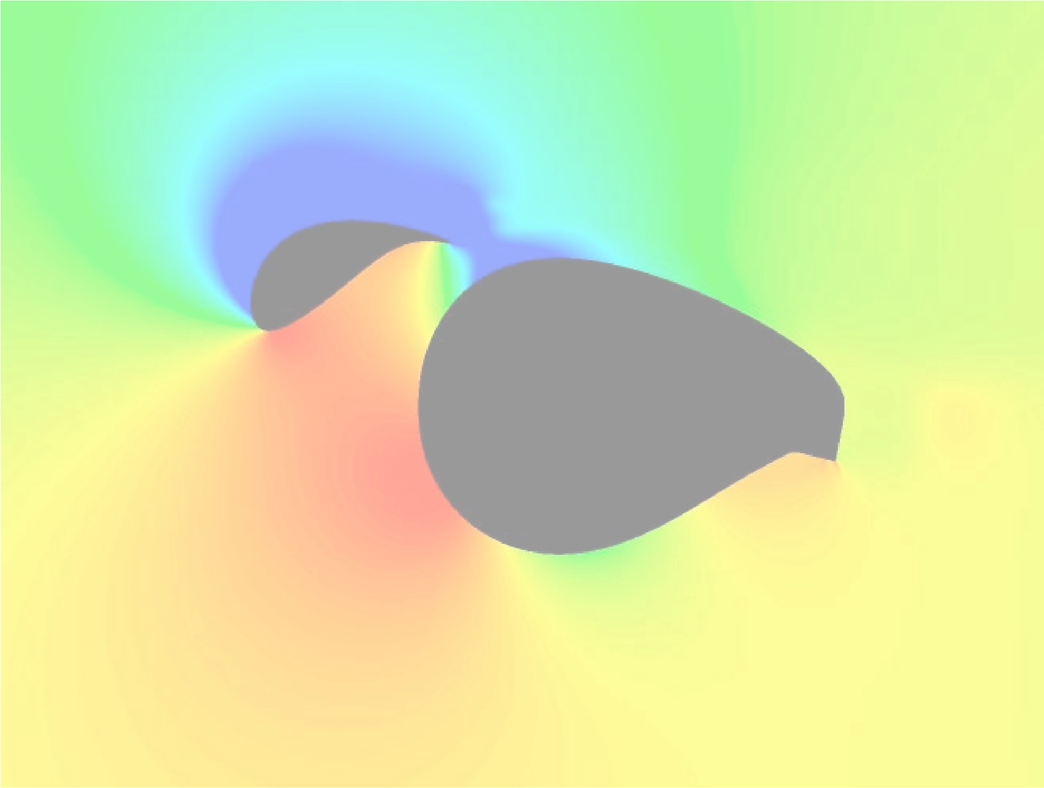
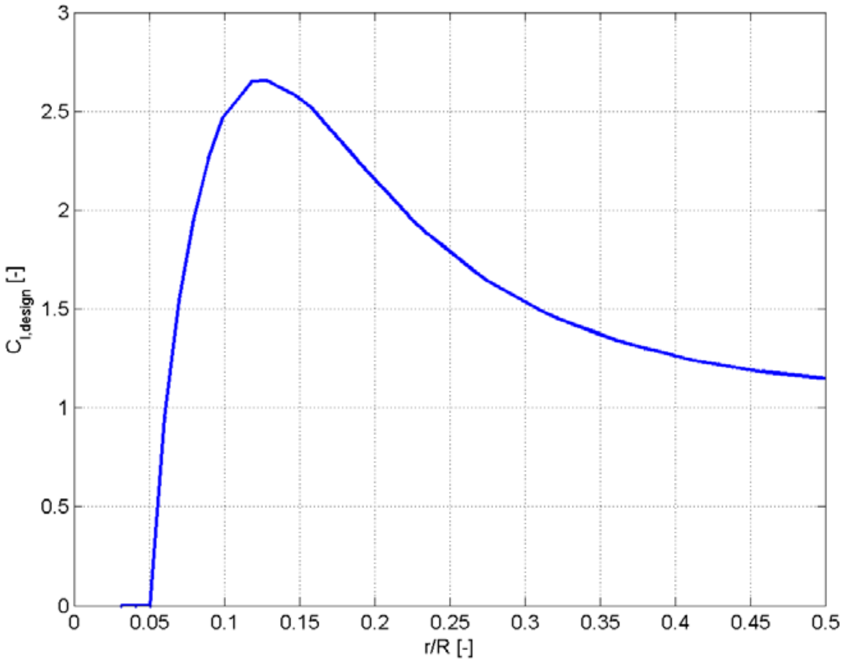


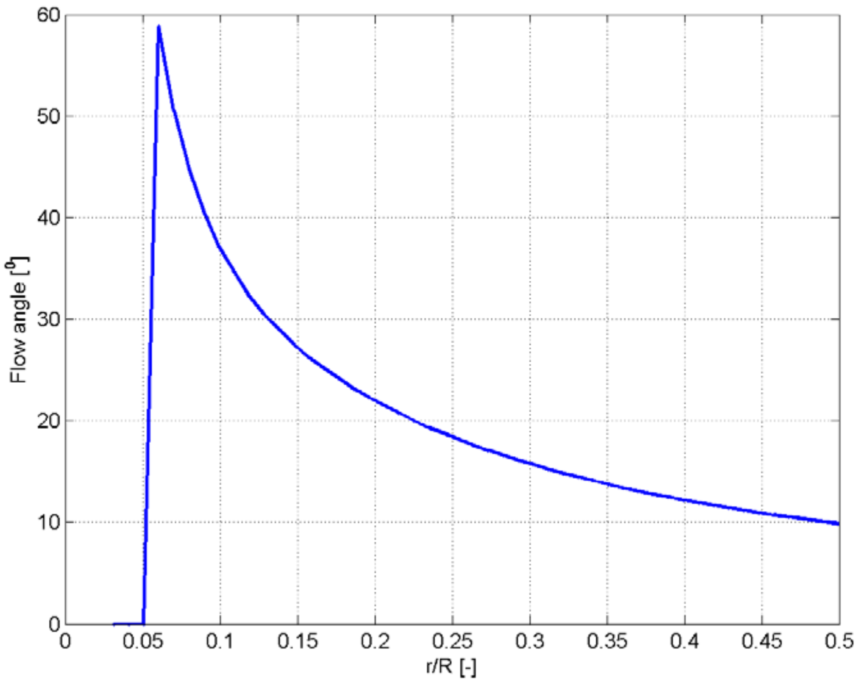
Results & Discussion

➢ Rotor design results from lifting line free wake method

Lift coefficient versus r/R



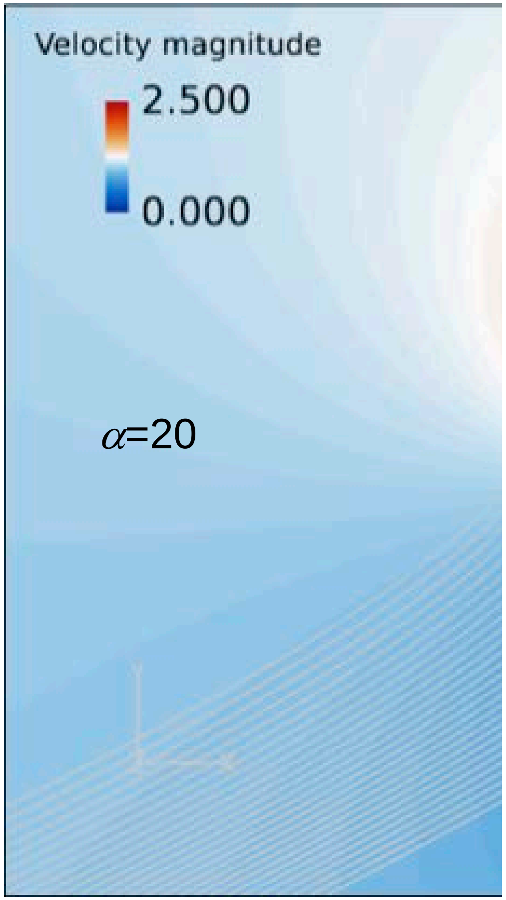
Flow angle versus r/R

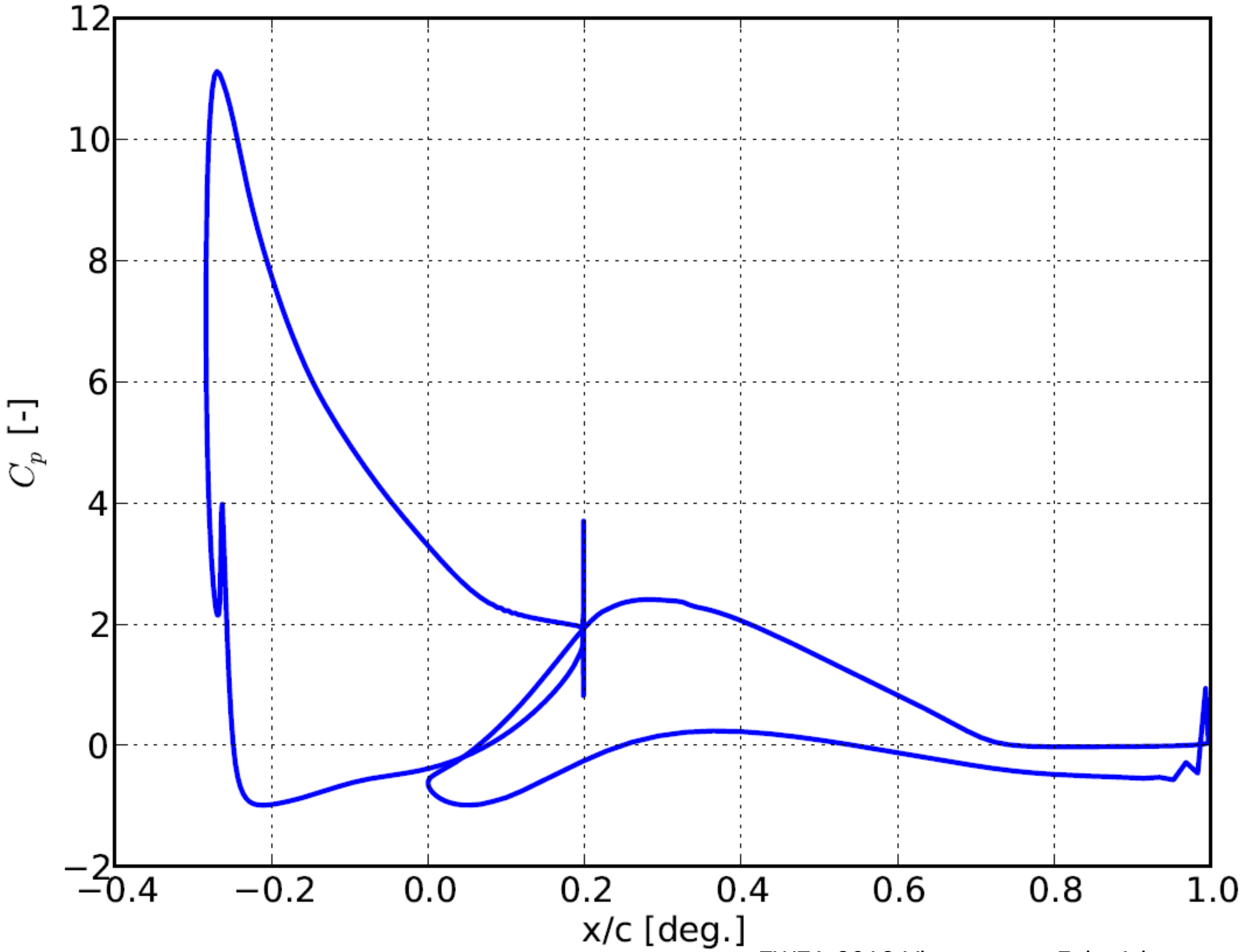


Results & Discussion

- Slat design (2D CFD) to obtain 2D crossectional shape of slats

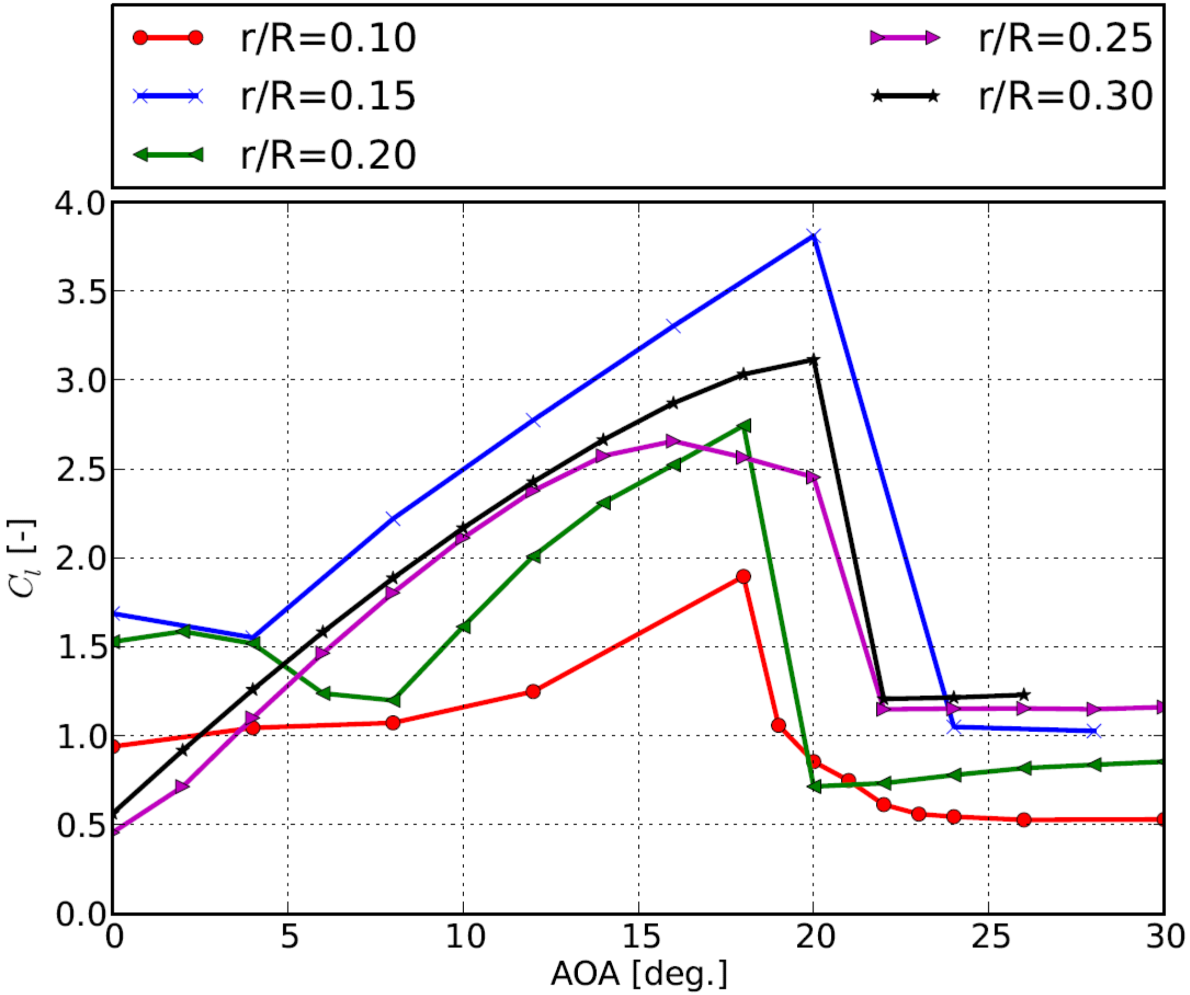
$r/R=0.15$ $t_{main}/c_{main}=0.77$ $c_{slat}/c_{main}=0.52$ $C_{l,max}>3.5$





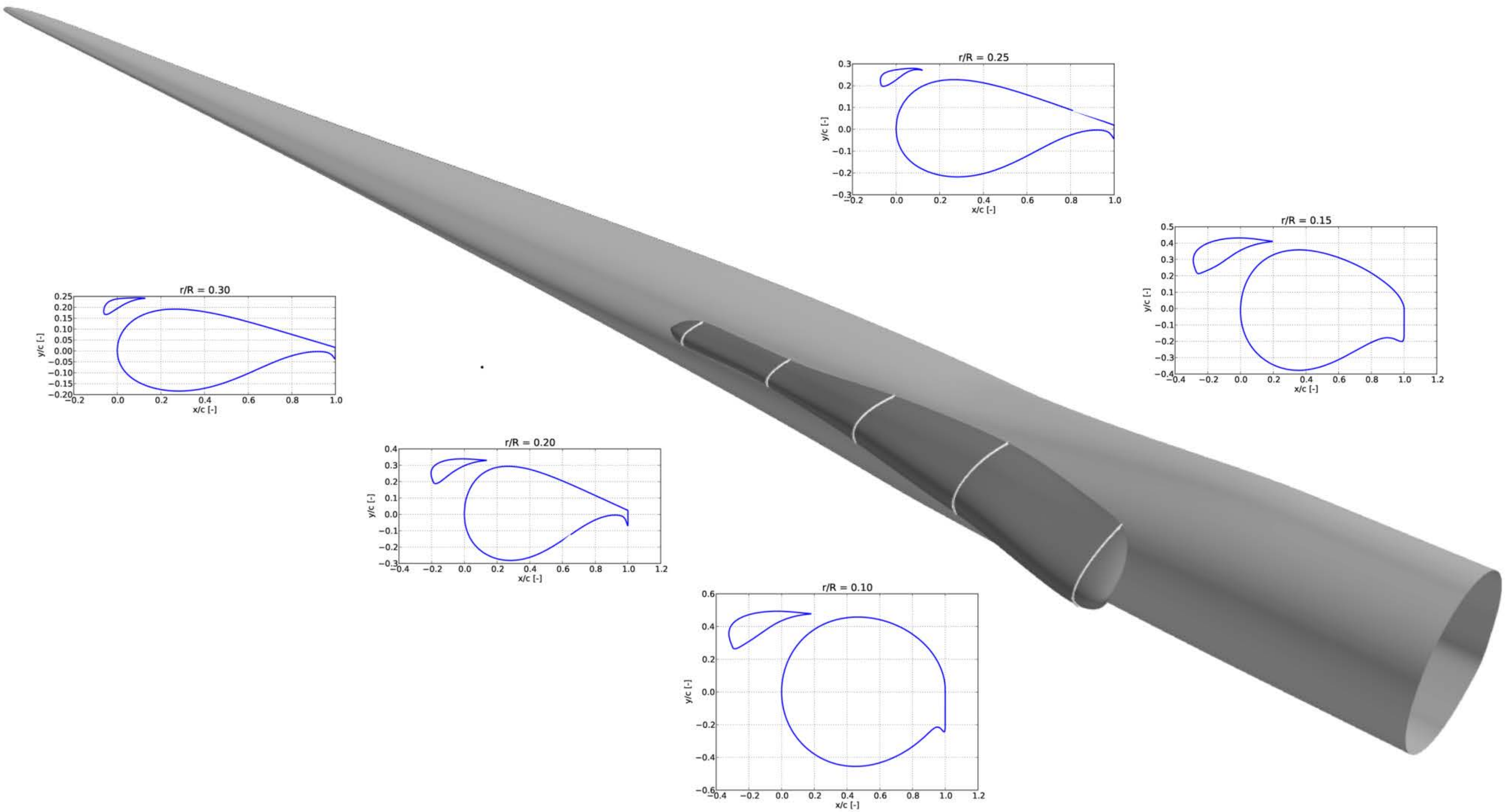
Results & Discussion

- Slat design 2D airfoil performances. C_l versus α



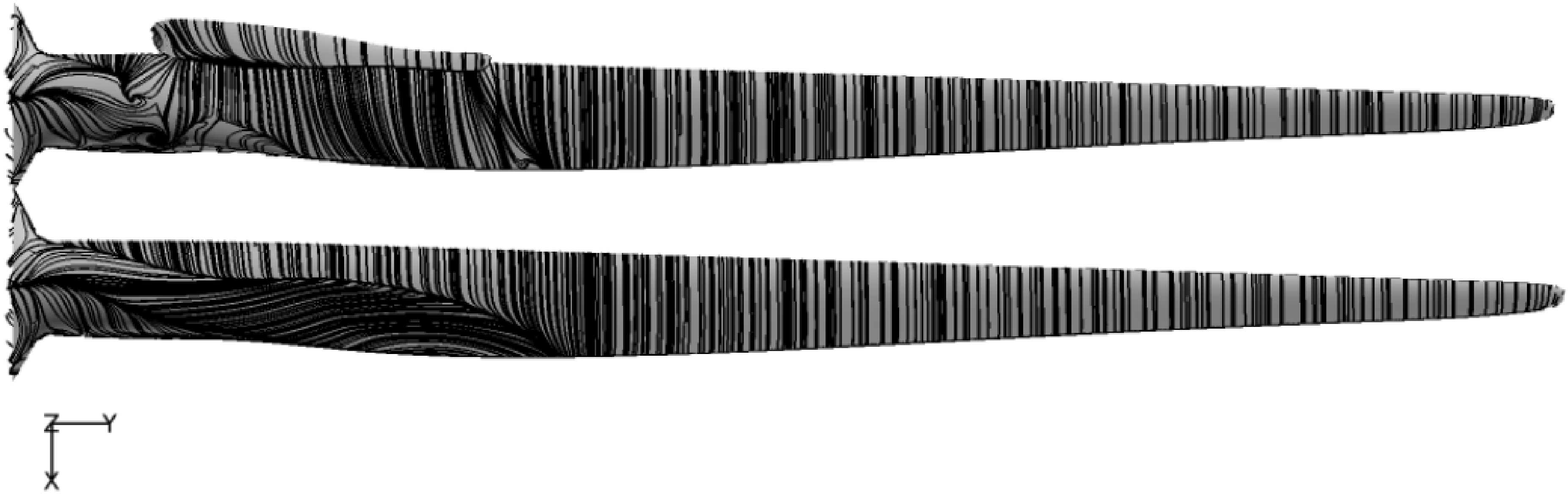
Results & Discussion

- Lifting line and 2D CFD results combined to get the 3D layout



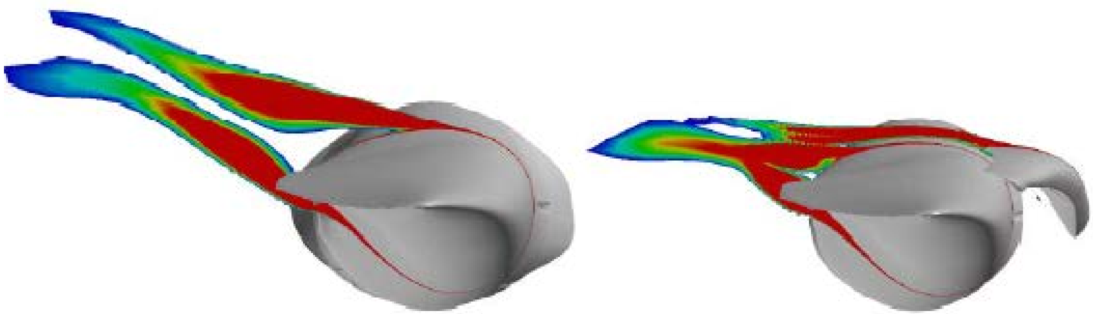
Results & Discussion

- Performance evaluation using 3D CFD: Surface streamlines



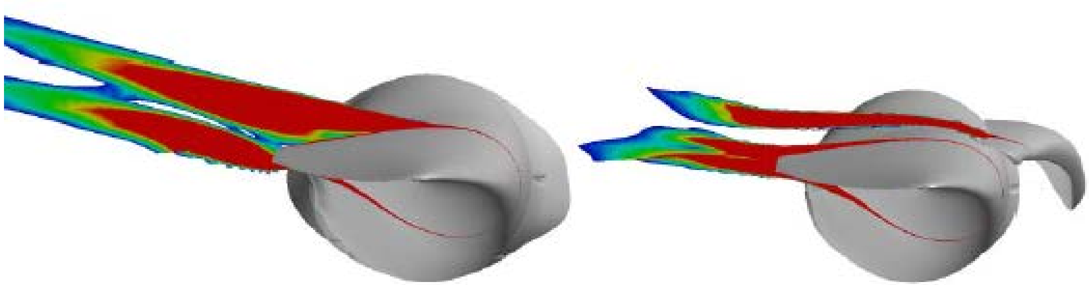
Results & Discussion

- Performance evaluation using 3D CFD
  Vorticity magnitude without and with slats



r/R=0.15

Without slats *With slats*

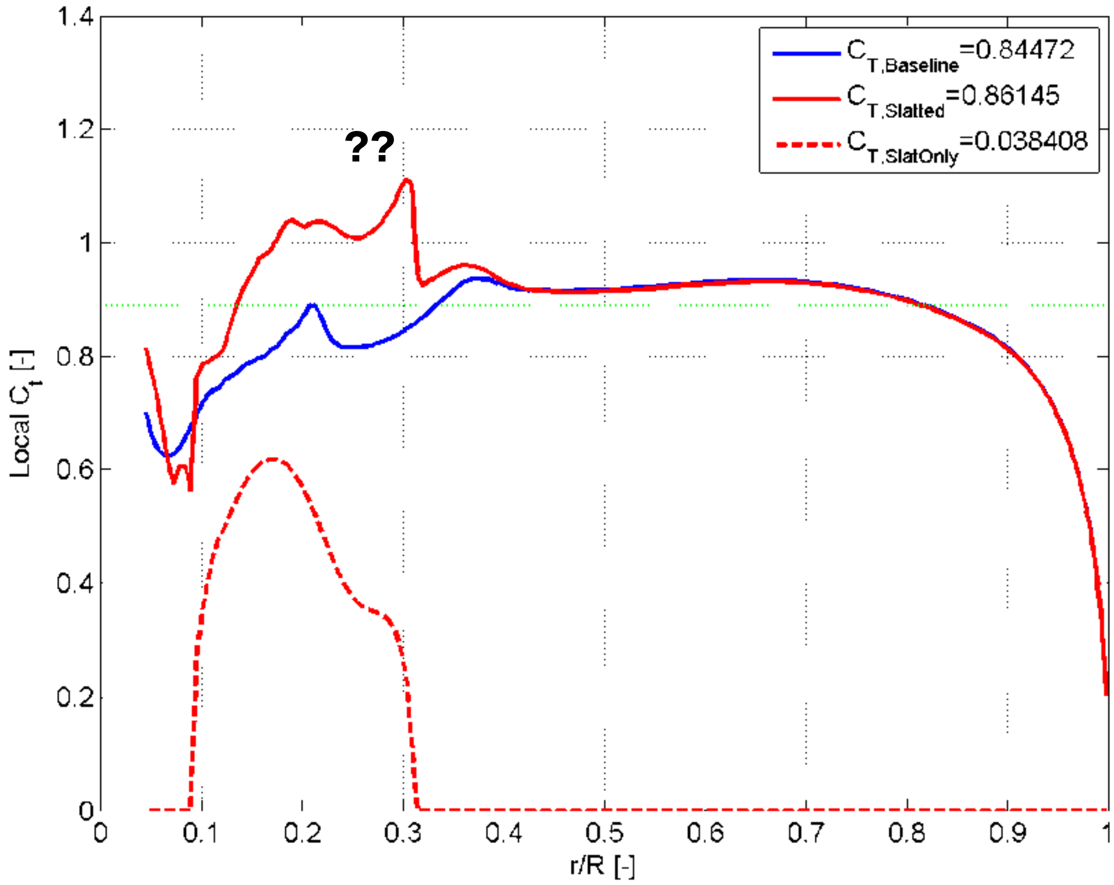


r/R=0.25

Results & Discussion

- Performance evaluation using 3D CFD
- Local thrust coefficient

$$\tilde{C}_t(\tilde{s}) = \frac{N_B F_{axial}(\tilde{s})}{\pi \rho V_\infty^2 R \tilde{r}(\tilde{s})} \qquad C_T = \int_{\tilde{s}_{root}}^{\tilde{s}_{tip}} 2\tilde{r}(\tilde{s})\tilde{C}_t(\tilde{s})d\tilde{s}$$

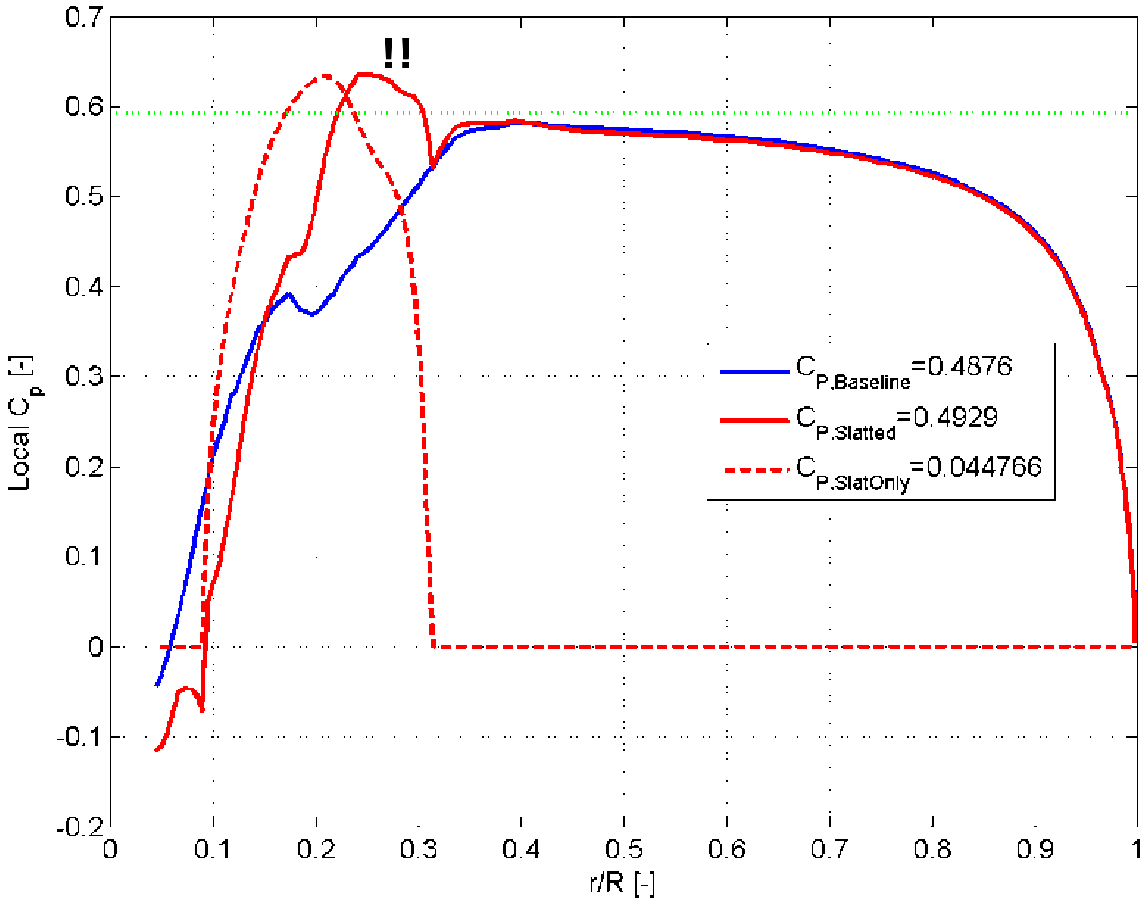


$\Delta C_T / C_{T,ref} = 2\,\%$

Results & Discussion

- Performance evaluation using 3D CFD

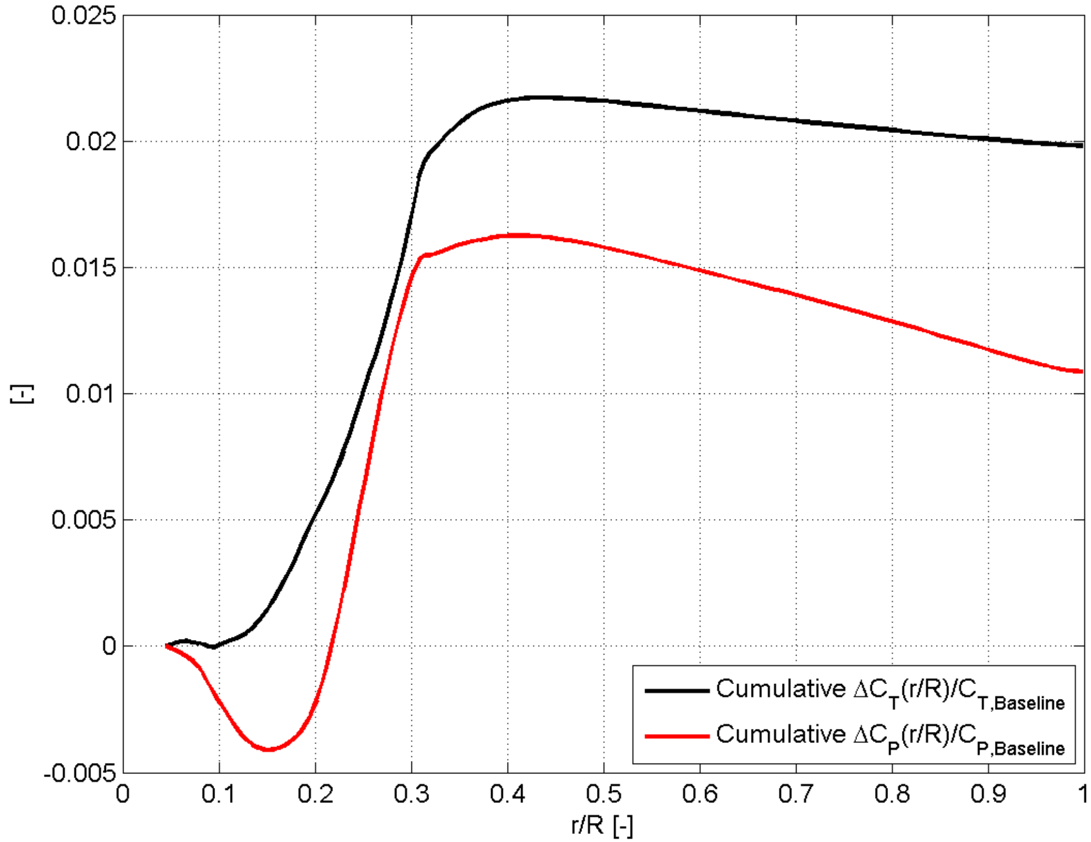
  Local power coefficient $\tilde{C}_p(\tilde{s}) = \frac{N_B F_{drive}(\tilde{s})\lambda}{\pi \rho V_\infty^2 R}$ $\quad C_P = \int_{\tilde{s}_{root}}^{\tilde{s}_{tip}} 2\tilde{r}(\tilde{s})\tilde{C}_p(\tilde{s})d\tilde{s}$



$\Delta C_P / C_{P,ref} = 1.1\%$

Results & Discussion

- Performance evaluation using 3D CFD
  Cumulative thrust and power coefficients



"Interesting" result:

Quite a large part of the power gained at the slatted radii (~1/3) is lost on the outer part of the blade!

This behavior is not captured in BEM results

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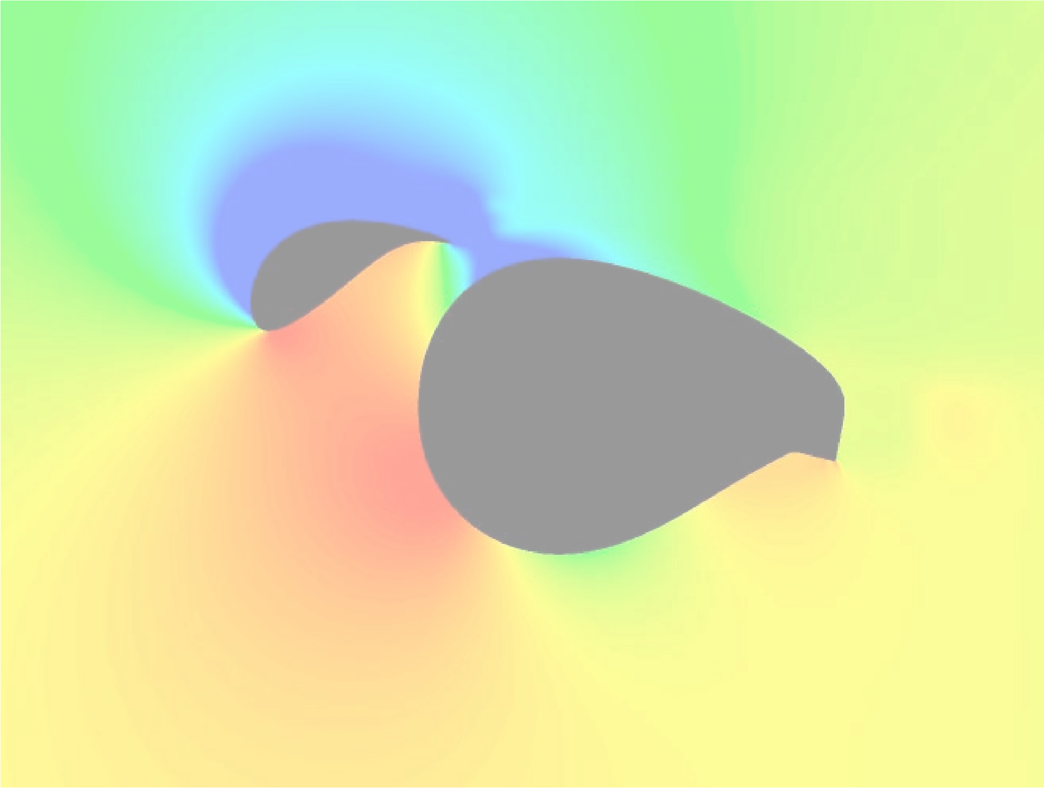

Conclusions & Outlook

- A one-point rotor/slat design method, based on lifting line free wake method in combination with 2D CFD optimization, was presented
- A new optimization framework for slatted airfoils using 2D CFD has been demonstrated
- A set of multi-element airfoils were designed for the DTU 10 MW reference rotor for 0.1<*r/R*<0.3
- For the first time, a 3D design of a rotor with slats is evaluated using CFD
- Due to a disagreement on the definition of profile coordinate systems, no definitive answer for the increase in C_P or AEP by the use of slats.
- However: $\Delta C_P/C_{P,ref}$=1.1% for this non-optimal case.
- Interesting 3D effects on the outer part of the blade resulting in a significant power loss

On the to-do list:

- Get agreement on all geometry definitions, and run the intended case
- Evaluate increase in C_P and AEP, and investigate C_T “cost”
- Evaluate how close LL/BEM computational tools get to the CFD result
- Is a final tweaking using 3D CFD needed in the design loop?
- 3D corrections for the slatted sections...